

## Communication Sciences in a University Environment

**Abstract:** Information processes and information processing systems are the principal concerns of investigators in many fields, including electrical engineering, neurophysiology, psychology, linguistics, genetics and mathematics. Studies in each of these fields contribute to understanding in the others, and each has a need for mathematical models and mathematical methods for describing and analyzing these processes. Studies of electrical communication and computational systems have provided the mathematical tools and understanding which are useful to the other fields. The related interests of this diverse group of scientists are examined and the activities of several groups in the Communication Sciences Center at M.I.T. are described.

For all of us who have been involved in communication problems and information processes, it is a great pleasure to see a laboratory dedicated primarily to research in this field, probably the first industrial laboratory assembled for just this purpose. Although the Bell Telephone Laboratories do an enormous amount of research on information systems, perhaps more than any other group in the world, it is also probably true that this was not the original intention of the Bell Telephone Company, and this new laboratory represents a conscious decision on the part of management to study communication processes.

This is not a surprising development. IBM's concern throughout its history has been the field of information processing. It was originally interested in the simpler—or what is now regarded as simple—computing problem, involving simple numerical processes. The underlying mathematical theory and the mathematical problems involved, and even the construction problems, encountered in early IBM machines were relatively simple compared to the present problems. As a matter of fact, the most advanced computing machines of the past were logically trivial compared to the machines now being built, and these certainly will be dwarfed by the machines now contemplated. For example, the early analog machines, which were the first problem-solving machines, were all predetermined and prewired by man and quite simple to operate.

As general-purpose digital machines were developed and became more complex, it was found desirable to use the same computing elements over and over. This made it necessary to give instructions to the machine, and this in turn led people to talk about machines that “think.” Most experts would not consider the present generation of machines capable of “thinking,” but many do dream

of the possibility of machines carrying out operations which have properties analogous to those described as thinking.

Information processing systems are but one facet of an evolving field of intellectual activity called communication sciences. This is a generic term which is applied to those areas of study in which the interest centers on the properties of a system or the properties of arrays of symbols which come from their organization or structure rather than from their physical properties; that is, the study of what one M.I.T. colleague calls “the problems of organized complexity.”

Scientists are increasingly aware of the fact that the underlying problems in a diversity of fields are basically similar; they involve the processing, storage, and transmission of information. There has developed over the past decade a close kinship among persons working in these related though disparate disciplines. Among the traditional disciplines involved are those of mathematics and logic, communications engineering, linguistics, acoustics, physics, neurophysiology and psychology, to mention a few. This meeting of mathematicians, engineers, and physicists witnesses the presence of chemists, linguists, librarians, and biologists.

I am going to discuss the role of a university in the field of communication sciences. Specifically, I am going to write about those areas of research and human endeavor to which the mathematical methods, computational techniques, and general understanding of communications apply and to which fundamental research in a university can make important contributions.

It is interesting that we should be examining the role of universities in this field at a time when we are dedicating a new industrial laboratory, for it is true that

industrial and university research are complementary. A university regards scholarship or learning, the creation of new knowledge, and teaching as its functions in society. An industrial laboratory doing similar work is certainly interested in understanding and in the creation of knowledge, but its motivation is different. To a large extent its concern is with problems whose understanding may ultimately contribute to the growth and welfare of the sponsor. In describing this new laboratory, the IBM booklet reads as follows:

*The product of an IBM research laboratory is the development of concepts that lead to new business machines, components and systems. In the planning of the San Jose Research Laboratory, emphasis was placed on giving the IBM scientist the most effective working environment possible.*

As science and technology have become increasingly complex, industry has assumed a responsibility for acquiring new knowledge. Research is becoming more and more expensive, and adequate investigation requires large groups. As these changes have occurred, industry has found that it can not depend entirely upon the universities, where it is incidental to teaching, for the fundamental work of supplying the technological base required for its continued economic growth. Consequently, we are witnessing the development of a number of research centers, similar to this one, which will augment, supplement, and in many instances surpass the amount of fundamental work that can be done in the university.

The actual work, particularly at a fundamental level, in an industrial or university laboratory may well be the same, but at the point where understanding is achieved a university staff commonly will lose interest in a problem; this may be just the point where an industrial group would begin an intensive exploitation of the ideas involved.

Additionally, a university provides an environment where the tentative and tender shoots of an idea may be followed far afield without question or explanation. The communication sciences provide an example of an area in which this freedom is particularly important, for one can confidently predict that during the course of the next two decades the results of research having as its basis the understanding of communication processes will be evident over an enormous range of human endeavors and may, in fact, have its most dramatic influence on the so-called soft sciences, that is, in the fields of economics, psychology, social sciences and related subjects, where basic theories are currently lacking, where models do not exist to explain complicated interactions, and where vast quantities of data need to be correlated or otherwise processed.

Ordinarily I am reluctant to speculate too freely or openly concerning the long-term consequences of research and discovery in the communication sciences, for the field is really just in its infancy, and promises made today are, at the best, highly speculative. Quotations out of context can paint an over-optimistic picture of the near future, particularly concerning the ease of achieving the dreams many of us share. However, the IBM management has had the vision and foresight to make a large commitment

to research in this field, and by indicating the endless future of this field, we can add our encouragement to their aspirations.

The fundamental difference between the communication sciences and many other sciences is that, though people in this field may be forced to study physical properties of systems, it is the organizational or structural properties which are of primary concern. Here there are new concepts to understand, and new mathematical tools are required and being created.

Developments of the past two decades in the mathematical and theoretical aspects of the communication sciences, particularly in the fields of electrical communication, electrical computation, data processing and automatic control, lead us to believe that the necessary tools to permit analytical studies of many of the communication problems in the broad fields are now emerging, and some of us are optimistic enough to hope that with development and growth, these new tools should allow increasing understanding of the more complicated problems of communication and control found in living systems.

Adequate theoretical models, followed by more adequate understanding of neural and social communicating systems, will make an important contribution toward the better understanding of problems of mental health and social relations. In addition, we believe that better understanding of the underlying theory, taken together with new electronic components already under development, will permit man-made information processing devices to be much more versatile, intelligent, and useful.

Men of curiosity throughout all history have focused their interest and intelligence on understanding the physical universe and the living organisms within it. The accomplishments of the Greek philosophers are well known to all. Some wanted especially to understand the motion of the stars, the nature of matter, the properties of fire and water. These early interests stimulated the development in the physical sciences, and most notably, mathematics.

The modern-day natural philosopher, the physicist, the chemist and the applied mathematician, have pursued the quest for knowledge about the physical world with a vigor and success that require no description. The scientific method with its interplay of experiment and theory, inductive and deductive reasoning, its challenge for mathematician and experimentalist alike, has provided the approach to an ever-widening understanding of inanimate nature.

During all stages of the development of the physical sciences, many workers were also concerned with the problem of the behavior of organisms. Nonetheless, in spite of much speculation about problems of thought and perception, individual and group behavior, and of the nature of life itself, until very recently comparatively little progress was made in the direction of understanding, controlling, and predicting events and phenomena in these realms.

Development of modern communication and computing devices has resulted in the construction and operation

of information-generating-and-processing systems which are, at least in part, amenable to constructive study. Early communicating systems, such as the telephone and telegraph, were sufficiently simple so that no analytical tools were required to properly design and build them. Trial-and-error methods sufficed in their design. However, communication and computing systems have become so complex that their development and an understanding of their behavior in operation are impractical without adequate theory.

I don't want to underestimate the role of the engineer or the inventor in this field, because I think it will always be true, especially in a field as complex as this, that innovation and invention will probably outrun the theory, but they cannot outrun the theory very far if one hopes to have continued growth and development.

Complicated though they are, man-made information-processing systems are primitive compared to any natural system available for study, so that understanding of the man-made systems undoubtedly is an important step toward the understanding of biological systems.

Modern electronic technology is assisting the research worker in biological and social communication fields in a second, equally important role by providing him with adequate measuring and computing devices that allow him to examine theories and models more objectively. That is, in furnishing him with tools ranging all the way from sensitive amplifiers and recording signals to computers, electronic technology is making it possible to test theoretical models of economic and social and logical systems.

I would like to divide the communication science problems into those that involve living systems and those that concern artificial or man-made information-processing systems. The living systems in turn have two categories: one concerned with the organisms themselves, that is, the arrangement and function of the unit cells and the molecules that make up the individual cells, and the second, the problems that are associated with the flow of information in neural systems; the question of brain function and the question of how the sensory organs perceive information and process it and abstract it before it is sent to the brain.

These foregoing are problems within the organism, the second category involving the problem of communication between human beings or other animals. Man obviously exists as a social animal only because he has evolved a number of good systems for communicating ideas or having ideas and for controlling group behavior. Spoken language is one such system, and the written language is another. More subtle are the economic and social organizations in which man lives and which continuously influence his behavior, while they in turn are reacting to his need; witness the continuous evolution of our social systems. There is an interplay between the man-made machines and the natural systems themselves, because the machines which we are talking about, communication systems, the telephone and teletype, the computing and processing machines, are all aids to communication between man and man.

Increasingly, we are allowing our machines to talk to each other, and as we look to the future, the things we are talking about here today will become realities. The things we are dreaming about, better telephone systems, automatic dictionaries, computers that "think," translating machines, and voice-operated typewriters are all conceptually possible today.

Finally, our machines will be able to solve abstract problems for us, problems which in the end they will have to formulate for themselves, because they will be too complicated for us to formulate.

None of the communication problems encountered in living systems are very well understood today, and the path to understanding in at least some of the areas listed will be very long and arduous. While the understanding and insights gained from study of man-made communication systems will be extremely useful to the investigator of living systems, and the research tools made available by communication technology are invaluable, it is important to realize that there exist very important differences between the two sets of problems, and I would like to stress that I believe that it is naive to hope that an understanding of how a computer functions, or of the most efficient way to transmit a television picture, or even how to design a machine that can solve logical problems, will automatically explain how the brain functions or why people respond as they do in a given social situation.

Cardinal to progress in all of the communication sciences is the development of the appropriate mathematics to be used in the development of new theory. Most people find the need for the discovery of new mathematics hard to accept. Nonetheless, it is a fact that recent developments in mathematical logic, probability theory, statistics, game theory, modern algebra, topology, set theory and the mathematical theory of information have been essential to the understanding which does exist of electrical communication, language, computing devices, learning processes, servomechanisms, and many other of the communication sciences, and further mathematical developments are required if progress is to continue.

It is useful to examine two related questions at this point. What is communication, and what is the commodity of communication; that is, what is the process and what do we communicate?

If we refer to Webster's International Dictionary, we find, "To communicate: to impart, bestow or convey, to make known, to give by way of information, to share in common, to make common to both parties or objects involved the knowledge or quality conveyed;" "Communication: intercourse by words, letters or messages, etc."

These definitions pertain primarily to human communication, though they are obviously general enough to apply equally well to communication between man and machine or between machines.

With the question of what is transmitted, we will have a greater difficulty. The dictionary actually gives us some help, but includes the movements of material things as in commerce. When we talk on the telephone or link a radar set to a computer, what is the commodity being handled?

When two people talk, they are making use of verbal signs. The signs in this case are words. The signs should normally have the same significance or meaning to both parties involved in the communication process. Signs may represent things, relationships between things, or relationships between the signs themselves. This, of course, is well known to all of you. An ensemble of agreed-upon signs constitutes a language, and communication is possible between individuals only to the extent that they do share a common language. As a matter of fact, much of the difficulty of human communication, written or verbal, comes about because words do not mean precisely the same thing to any two people.

For example, rain may mean one thing to a person who has only experienced a gentle, warm shower followed by lush greens of spring and something quite different to a person used to monsoons. Words take on subtle meanings from a lifetime of use.

We often have difficulty isolating the communication symbols. Of course, in machine language it is easy to be very specific about the meaning of symbols.

Written language makes use of a restricted number of symbols, signs for sounds used in speaking, which make it possible to record the verbal messages. These new signs—the written language—may, of course, be used directly for communication between individuals. Language is also necessary for an individual to be able to think, i.e., communicate with himself.

Language, which most people use with little or no effort, at least when speaking, is an extremely complicated process which is only partially understood. This complexity and lack of understanding is shown very clearly when we attempt to tell a computing machine how to translate text from one language to another. This is something which a machine should be able to do, though so far it has not been done successfully; the difficulty is man's, not the machine's. We do not have an adequate understanding of the organization and operation of language to describe the translation process to the machine. There is a similar difficulty when we attempt to deal with problems of information retrieval and data storage.

I do not think that the difficulty comes from our inability to make machines with adequate storage or speed of operation. I believe that if we wanted  $10^8$  or  $10^9$  bits of storage, IBM would gladly roll up its sleeves and provide it in a machine. The difficulty comes from the fact that we do not know how to use such capabilities, and, of course, this is the theoretical challenge of the field.

When electrical communication is employed, the symbols or signs are the electrical signals. The electrical signals may be used to represent acoustical signals or letters of the alphabet or the position of a shaft or any other variable which can be expressed as a single valued function of time. They may be signals which convey information by means of a varying magnitude of an electrical voltage, as in the case of telephone transmission, or as coded combinations of simple on-off signals, such as the dots and dashes of Morse code. Note also that the actual physical medium used for transmission does not alter the

information content of the message. The letter "A" is represented by a dot and a dash sent in succession. It can be sent as an electrical signal, as a smoke signal, by semaphore flags, by blinker lights, or as marks on paper; the medium doesn't matter—the important thing is that there be agreement between sender and receiver concerning the significance of the signs used for communication.

In point-to-point communication systems, such as the telephone or teletype, electrical means are employed to get symbols from one physical location to another. In servomechanism systems, electrical information is used to control mechanical motions; in computers, electrical signals are used as input information and as the medium in which the internal language is conveyed, while the machine manipulates the input information to yield desired information.

Computing machines may perform both numerical and logical operations. For example, a digital computer can be made to perform the mathematical operations of addition, multiplication, integration, differentiation, etc., when given the proper instructions. It may also be made to store quantities of non-numerical information, as for example the abstracts of all the journal papers in a given field, and then be asked to reproduce all of those bearing upon a specific subject.

Both telephone systems and computers are elaborate networks with many possible interconnections between components. For proper operation, routing and switching of messages must be handled rapidly and unerringly, and as a consequence, automatic switching systems have been developed to perform these functions. For example, within a computer, the program may require taking a piece of data out of a slow memory, putting it into a rapid access memory, thence into an arithmetic unit for manipulation, back again into the fast storage, etc., many, many times until the solution of a given problem is completed.

This group of electrical problems has received much attention from electrical engineers and mathematicians during the past two decades, and they now have sound mathematical foundations. The existing mathematical theory falls into four rather distinct categories:

- a) Mathematical communication theory.
- b) Network theory.
- c) Feedback or control theory.
- d) Switching circuit and computer theory.

These developments, together with a number of pure mathematical developments, provide the mathematical background for all of the communication sciences. I would like to review each of these subjects briefly.

### **The mathematical theory of communication**

The field of electrical communication has recently been provided with a satisfactory theoretical foundation. This is primarily due to the work of Professor Claude Shannon, formerly of the Bell Telephone Laboratories, now at M.I.T., and Professor Norbert Wiener, also of M.I.T.

While early communication engineers did extremely well in the development of telephones, radio, and other

electrical communication devices, they had little or no real understanding of the commodity "information," which they were transporting. Their designs were based largely on good intuition and experimentation, ingredients which, it should be noted, remain very important today.

There are two properties of any electrical transmission channel, be it wire or wireless, which must be tailored to a given communication task. One is the bandwidth of the channel, the other is its signal-to-noise ratio. The bandwidth of the channel is a measure of the range of frequencies which it can transmit without distortion. Different types of messages require different bandwidths for adequate transmission. A Morse-code transmitter requires only a few cycles per second of bandwidth, a telephone 3,000 cycles per second, a hi-fi phonograph or radio 15,000, a television system 4,000,000 cycles per second.

The results of such experiments were intuitively satisfactory though not quantitatively understood. The bandwidth of a circuit is a measure of the rate at which a signal can change from one amplitude to another, that is, the rate at which the channel can accept new signs or symbols; and so it is not surprising to find that a voice channel requires more bandwidth than a Morse-code channel or that a television system, which is capable of sending vast amounts of information, needs a channel a thousand times wider than that required by a single telephone circuit.

Though these observations appeared reasonable, no real understanding existed of the relationship between properties of the signals being processed and the circuit requirements for adequate transmission.

Noise in the channel introduces a second consideration. Noise is understood to mean random electrical signals which exist in all actual systems. The effect of certain kinds of noise, such as static received on a radio set of interference generated by electrical machinery or other communication systems, can be dealt with by clever design, but even if such effects are eliminated, a residue of noise remains. This residual noise is the result of the fact that the various electrical devices, wires, vacuum tubes, etc., function because of the presence of large numbers of electrons having both random and directed components to their motion. The random or unpredictable component of the velocity adds a continuously variable, unpredictable component to the electrical signals. Such random noise signals are found at the output of all transmission lines, antenna systems, transistors, vacuum tubes, and most other electrical components. The magnitude of this random signal at the output of a telephone line is of the order of a millionth of a volt, so that in many applications it is not observed.

It is easy enough to see that transmission quality is degraded as the ratio of signal energy to noise energy is reduced, and it is relatively simple to determine experimentally what noise level can be tolerated for any given communication service. Obviously, increasing noise in a communication channel reduces the amount of information that can be transmitted, but how?

Further work is needed to provide a quantitative defi-

nition of a unit of information so that such questions may be properly studied. Before Shannon published his mathematical theory of communication, such a unit did not exist. Communication engineers were processing a commodity which they could not see, feel, measure, or even define. As long as communication systems were simple, this state of ignorance was not very troublesome or costly; however, as systems grew more and more elaborate, as they did, for example, in automatic gun director systems involving the interconnection of radars, communication circuits, computers, servomechanisms and guns, the effects of errors introduced by noise or inadequate circuit bandwidth could be catastrophic. Stimulated by such wartime problems, many able theorists studied them. The most notable contributions to their comprehension were made by Wiener and Shannon.

Wiener provided a mathematical theory explaining how to design an optimum system when faced with a signal corrupted by noise. Shannon provided an acceptable definition of a unit of information, and using this measure, showed what the theoretical capacity of a given channel should be in terms of its bandwidth and signal-to-noise ratio. He also demonstrated that with the proper choice of signs or symbols, it is theoretically possible to send messages without error at a rate equal to the theoretical capacity which he had found.

Shannon chose the simplest situation possible for his unit of information, the choice between two symbols which are equally likely; that is, the choice in which there is no prior knowledge or data to make the receiver anticipate one event rather than another.

This basic unit is called the "bit," a contraction of the name "binary decision." The binary decision is defined as a selection of one of two equally likely choices. In many cases the choice is made from among a much greater selection. Letters are choices from a set of 26 symbols, words are selected from some indefinite but large set of symbols, a specific electrical voltage may be one of a large number of possible voltages. In all such cases, the selection may be made, as we have already seen, by using a series of binary selections to represent a given symbol. Most information sources do not provide a sequence of equally likely symbols, and in that case, the mathematical theory gives greater weight to the less likely symbols.

Before leaving this subject, I would like to explain briefly the manner in which the theory also takes account of the effect of noise in the transmission channel. A given transmission system is usually capable of handling a definite range of signal amplitudes or voltages before it overloads. Each level which can be distinguished at the receiver might be regarded as a distinct symbol. Noise in the circuit establishes a limit to the number of different levels into which the permissible signal range can be divided. The random variations in signal caused by the noise have the effect of changing what would otherwise have been a definite signal amplitude, corresponding to a specific input signal, into a signal occupying a fuzzy region where the output might appear. The greater the magnitude of the noise, the larger the fuzzy region. If

two input signals are sufficiently alike to cause the uncertain regions corresponding to each of them to completely overlap, they cannot be distinguished at the output. It is almost correct to say that signals whose energies differ by less than the average noise energy cannot be distinguished; this means that the number of distinguishable symbols or signs available is equal to the ratio of the signal power to the noise power. The greater the noise for a given signal range, the fewer symbols are distinguishable; in the limit when the noise exceeds the signal level, not even one selection can be made. This relationship is exactly specified by the mathematical theory of communication. From the foregoing we see that the number of distinct levels, and therefore the number of "bits" of information, which can be transmitted by a single measurement, is a function of the signal-to-noise ratio.

We have yet to see how the bandwidth affects the rate at which information may be transmitted. We have just found the amount of information that can be transmitted by sending a single electrical voltage. If we now determine the number of distinct voltages that can be transmitted per second, the total number of bits a channel can transmit per unit of time can be found by multiplying this number by the number of bits transmitted by sending a single signal amplitude.

The rate at which an electrical signal can build up or die out in an electric circuit depends upon its physical properties. A narrow-band circuit can change from one signal level to another only a few times per second and, consequently, convey only a few signs or symbols per second. A circuit whose bandwidth is 10 cycles per second can handle approximately 10 distinct symbols per second. If we try to send at a faster rate, the symbols blur together and cannot be distinguished one from another. A million-cycle-per-second circuit can handle a million symbols per second.

The development of this theory has excited not only communication engineers who would naturally be expected to welcome it, but also scientists interested in the diverse fields listed earlier having a common interest in communication processes.

Why should this mathematical development have such a great impact? There are several reasons. One of the most important things that the Shannon development provided was a precise and understandable model of the communication process, one which makes it possible to understand, at least conceptually, a wide range of problems.

For communication channels which conform to the restrictions of the theory, it provides a precise means of computing the maximum rate of information transmission. In this respect the theory is similar to the second law of thermodynamics. It sets upper bounds on the capability of a given channel, but unfortunately it does not tell how to design or build equipment that will perform as well as the theory predicts. In fact, one of the interesting problems that communication engineers are currently working on is the design of a set of symbols which will permit transmission without error over a noisy channel in a manner predicted by the theory.

I have discussed this one facet of the theory which exists in the communication sciences (in some detail) in order to give you a glimpse of the nature of the theoretical problems which are involved.

I will now review, rather briefly, the other concepts drawn from modern electrical technology, which have contributed to the present level of understanding of communication problems.

### Network theory

Electrical currents are ordinarily guided from one point to another by wires. The electrical behavior of an electric circuit is determined by both the properties of the elements of which it is composed and the manner in which the elements are interconnected.

Adequate mathematical theory exists to permit analysis of the most complicated electrical networks. In fact, similar mathematical methods are used to study the interconnection of power systems.

Electrical networks are represented, for analysis, as a collection of node points joined together by the various circuit elements.

When an electrical engineer studies such a network, he wants to know what effect a signal impressed upon one node will have upon all of the other nodes in the system. The first node may be closely coupled with some of the others, and then a signal impressed upon it will have a large effect upon them. The coupling with other nodes may be small or nonexistent, in which case a large excitation at the first node will have little or no effect on the others. The mathematical theory shows that the properties of networks are determined entirely by the interconnections between nodes rather than by properties of the nodes themselves.

### Feedback or control theory

One of the most important electrical developments of the last two decades is that of the servomechanism or feedback control systems. In elementary form such systems have in fact existed for a long time. A basic property of all feedback systems is the ability to sense or measure a variable to be controlled, compare its actual value with that desired, and then take appropriate action to reduce the discrepancy or error.

A simple feedback system with which we are all familiar is the thermostatic temperature control system employed to regulate the temperature of our homes. A simple temperature-sensitive sensing element determines whether or not the temperature of a room is above or below the temperature for which it is adjusted. If it is below, it turns a heating system on; if it finds the temperature high, it shuts the heating system off, and in this way succeeds in maintaining a relatively constant room temperature.

A more sophisticated servomechanism is the automatic pilot which has been used for many years to control the course of ships at sea. Here a sensing element measures the difference between a ship's course as indicated by a compass and the desired course. When the device senses



an error, the steering motor takes corrective action and returns the ship to the desired course. A similar though more complicated system is used aboard aircraft to relieve the pilot from the necessity of routine flying.

Error-correcting systems such as these described must be designed properly or they may actually increase rather than decrease errors. Improperly designed systems may overshoot the desired position or hunt violently about for the proper position.

Mathematical theory exists which provides a basic understanding of such feedback systems and enables an engineer to design a system free of the troubles described above.

Norbert Wiener recognized that such feedback or error-correcting processes exist in biological and social systems. He pointed out that some such mechanism must be provided in any goal-seeking system which is to succeed. The study of feedback systems in animals and machines he christened *cybernetics*, the title of his now famous book on this subject.

### Computing machines and switching theory

The final component of the communication science field is the theory of the logic of computing machines, switching circuits and relay circuits. The foundations for effective techniques in these areas were laid down by Shannon for the logic of switching and McCulloch and Pitts for the logic of neurology. Turing provided the basic theory for the digital-computing machine.

This work, taken together, has given rise to significant developments in mathematical probability theory and particularly in the study of stochastic processes of increasing complexity. These processes, as already indicated, are encountered in problems of coding, of efficient transmission of information, of cryptography, of design of computers and automata, in the analysis of speech and language, in the transmission of signals through the nervous system, in the study of the behavior of groups and of learning itself.

The theory of switching circuits, resting on symbolic logic, is growing rapidly as digital computers become increasingly elaborate. More recently von Neumann's theory of games is being applied to handle questions of strategy in many of the arts of communication, including the programming of machines and the interaction of men. We are at present confronted by questions concerning systems so complex as to require new modes of analysis.

As I pointed out in my introduction, the computers, as they evolve, serve two roles important to the entire field. First, they provide a means of studying systems which are well defined but too complicated for an unaided human to study efficiently. Second, they serve as a source of models which provide a conceptual framework for the study of other complicated systems.

These developments in the communications area took place in a period during which the life sciences, the behavioral sciences, and the social sciences not only gained in importance in our society, but also underwent significant changes. The life sciences came to depend for their instru-

mentation more and more upon physics, chemistry, and electrical engineering. Refined instruments extended the experimental capacities of biological scientists; they did not, however, provide for appropriate methods of handling the data or for models appropriate to living systems. Behavioral and social scientists left the realm of speculation and became oriented towards the collection of empirical data. They too ran into the problem of appropriate mathematical techniques and models; the most theoretically inclined among them came to the conclusion that the mathematics that had served classical physics so successfully could not be expected to suffice here.

I am now going to describe briefly current research in several related areas to show the scope of activities in this field.

### Biology, electroneurophysiology and biophysics

Many analogies have been suggested between the nervous system and various statistical communication and computing systems, and many workers have occupied themselves with the formulation of various probabilistic models for the activity of the nervous system and with experiments designed to check such models. At M.I.T. there are several groups active in this field. One such group is that headed by Professor Rosenblith and Norbert Wiener. They are currently studying the way in which the nervous system of humans and animals processes and analyzes sensory information, such as sound. Many of the statistical "computing processes" which can be conveniently studied in the auditory system also occur in many other parts of the nervous system; consequently, the knowledge gained is generally useful.

The group has developed a number of special electronic devices to permit more effective analysis of the electrical signals from the nervous system, one such device, a semi-automatic correlator, being used for the study of various types of brain potentials. This work, which is being done in cooperation with the Massachusetts General Hospital, is yielding much exciting information, and the machine gives promise of being an important new diagnostic tool.

A second group, headed by Dr. McCulloch and including Walter Pitts, is investigating fundamental processes involved in the transmission of neural impulses and in the specific organization of the neural system. One extensive project of the group has been a study of the operation of the synapses on neural relays which function much as vacuum tubes do in communication and computer systems. These building blocks of the nervous system can have many of the properties of the elementary units of a computing machine and are capable of functioning as repeaters, coincidence units, delay units, adders, etc. The group has developed a theory of synaptic action based on the physical configuration and electrical properties of the units in conflict with existing theories which require the action of special chemicals to explain the neural behavior. Experiments are under way to test these exciting new hypotheses. Experiments in this field involve difficult measurements and sensitive instruments because they are attempting to make electrical measurements

inside of living nerve cells by delicate microelectrodes and amplifiers of great sensitivity. New tools, such as bipolar microelectrodes, voltage and current clamps, etc., are being developed to permit investigation of more involved sections of the nervous system.

In addition to the research on the individual components of neural systems, some relatively simple arcs of circuits in the nervous system are also studied. Reflex arcs in the spinal column of the cat have been investigated; also, the information processing system associated with the eye of the frog. The group has also investigated the effect of various chemicals and drugs on the behavior of components of the nervous system. Of particular interest to persons interested in the design of complex information-processing systems is the question of the high degree of reliability that has been designed into the human animal in spite of variable behavior of the individual elements that comprise the system.

### **Linguistic studies**

Not only is language the most basic vehicle of human communication, it also underlies the most important, if not all, other forms of communication among men. Writing and its various derivations (telegraph codes, etc.) are best thought of as recodings of the spoken word.

A number of interesting problems relating to human communication are being studied. Speech, though acoustically a quasi-continuous event, can be recoded in terms of discrete symbols. All forms of writing make use of this property of language: in alphabetic writing systems, like those in common use in much of the world, the code units symbolized by the letters are with some exceptions what linguists call "phonemes," while words are signalled by the "space;" in writing systems like those employed by the Chinese, many words are symbolized by separate symbols.

The existence of various levels on which language can be coded in terms of discrete symbols must be postulated for many reasons. An understanding of the physical operation involved in the process of writing, i.e., of a procedure of recoding the highly varied and continuous acoustic signal into a small number of discrete units, will provide important insights into the understanding of speech perception by man.

The fact that speech is highly resistant to distortions of various kinds suggests that various kinds of economies can be achieved in transmission by the proper kind of processing. A deepened understanding of the nature of the information-bearing elements in speech will allow us to design for such economies in a systematic manner.

The process of translation from one language into another is an extremely interesting problem that is being investigated. Translation involves equating linguistic structures pertaining to two different languages. In some instances these equations are obvious; in others, they are extremely complicated. What is sought is a procedure for analyzing the grammatical structures of different languages in such a way as to make statements of such equivalence possible.

In closing, it is appropriate to add a few more words about the role of computation and its importance to this whole field. It is from the field of computer design, switching theory, and the study of automation that we may expect some of the most significant developments of the next decade.

It appears that we will see significant applications to linguistic analysis and information retrieval systems as well as important contributions to the understanding of very complex information systems.

*Received May 27, 1958*